

****TITLE****

*ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR***

****EDITORS****

HI Signatures of Reionization

Paolo Tozzi

Oss. Astronomico di Trieste, via G. B. Tiepolo 11, 34100 Trieste, Italy

Abstract. The exploration of the end of the Dark Ages will be one of the most exciting field of the next decade. While most of the proposed observations must await the next-generation telescopes, the observational window of the redshifted 21cm line offers the possibility to investigate the physics of reheating and reionization on a short term. Here we describe several possible signatures detectable in the wavelength range 100-200 MHz. Among the physics that can be investigated: the epoch of reheating and reionization; topology and timescales of reheating; the nature of the ionizing sources; the baryon distribution at redshift $z \sim 10$. Such a good deal of information is within reach of present-day, or near-future radio facilities.

1. Exploring the Dark Ages

The Dark Ages are ended by the appearance of the first stars and/or quasars, that reheat the diffuse cosmic baryons and then reionize the Universe (see Rees 1999). The reionization is defined as the epoch when the volume-filling factor of HII regions is $\simeq 1$, and the Universe becomes transparent to ionizing radiation (for an extensive review see Loeb & Barkana 2001). The absence of a Gunn-Peterson (GP) effect in the line of sight of distant quasars, put the epoch of reionization (z_{reion}) at redshifts > 5 . To date, there are little additional constraints on the physics of the cosmic baryons at such high redshifts. This is also due to the complexities involved by any theoretical model that must include the nature and the birthrate of the first luminous objects, their spectrum and emissivity, their feedback into the surrounding Intergalactic Medium (IGM), etc.

A significant step forward has been recently obtained with Keck spectroscopy of the most distant SLOAN quasars (Becker et al. 2001; Djorgovski et al. 2001). The presence of a sudden increase in the Ly α opacity between redshift 5 and 6 may indicate that the Universe is approaching reionization at $z \sim 6$. However, Barkana (2001) pointed out that, due to the high Ly α opacity, these observations are also consistent with a post-reionization phase, and that a conclusive proof requires the observation of similar GP absorptions along several additional line of sights. Alternatively, the observation of smoking-gun signatures has been proposed. Among them: detection of scattered Ly α emission around sources beyond z_{reion} (Loeb & Rybicki 1999); features in galaxy number counts at $z > z_{reion}$ (Barkana & Loeb 2000). These observations would be effective probes of the physics of cosmic baryons and of the nature of the first ionizing sources at the same time, but they must wait for NGST and/or SIRTf,

which will be operating at the end of this decade. Signatures of the reionization are expected also in the CMB. MAP and Planck can probe the optical thickness at z_{reion} in the 30–150 GHz range. In particular, fluctuations on ≤ 0.1 degree reflect the topology of reionization. However, such measures are highly degenerate with cosmological parameters.

It is clear that the investigation of the Universe at $z \simeq 10$ is a difficult task with present-day facilities. In this situation, the observational window offered by the redshifted 21cm line can open much of the Universe to a direct study of the reheating and reionization epochs. In the following we will discuss some observations of HI at high z that can shed light on many aspects of these processes.

2. The History of the Cosmic Baryons

In this section we outline a simple scenario for the thermal history of the diffuse cosmic baryons in the high- z Universe, and we show under which condition they emit in the 21cm line.

During the Dark Ages ($z > 10$), most of the baryons of the Universe are distributed uniformly. The typical density contrast on scales $> 1 h^{-1}$ Mpc is still in the linear regime. The temperature of the diffuse baryons, experiencing only adiabatic cooling since the decoupling from the cosmic background radiation, is about $T_K = 0.026 \times (1+z)^2$ K (Couchman 1985), which, at redshift $z \simeq 10$, is one order of magnitude smaller than the CMB temperature $T_{CMB} = 2.73 \times (1+z)$. The spin temperature T_S of the cosmic baryon is defined via the ratio of the population of the triplet and the singlet state of the spin transition originating the 21cm emission. In absence of any coupling, the spin of the IGM is in thermal equilibrium with the background radiation, and $T_S = T_{CMB}$ on a very short timescale. To observe the 21cm emission from HI against the CMB, we need some process that decouple T_S from T_{CMB} . Collisions are ineffective, since the density contrast on Mpc scales is too low (Madau, Meiksin & Rees 1997).

There is, however, an efficient mechanism that makes HI visible in the redshifted 21cm line: the Wouthuysen–Field effect (WT). In this process, a Ly α photon field mixes the hyperfine levels of HI in its ground state via intermediate transition to the $2p$ state (see Appendix in Tozzi et al. 2000). The process effectively couples T_S to the color temperature T_α of a given Ly α radiation field (Field 1958). The color temperature is easily driven toward the kinetic temperature T_K of the diffuse IGM due to the large cross section for resonant scattering (Field 1959). Therefore the spin temperature can be written as:

$$T_S = \frac{T_{CMB} + y_\alpha T_K}{1 + y_\alpha}, \quad (1)$$

where $y_\alpha \simeq 3.6 \times 10^{13} P_\alpha / T_K$ is the Ly α pumping efficiency, and P_α is the total rate at which Ly α photons are scattered by an hydrogen atom.

Thus, the diffuse IGM at very high redshift (between recombination and full reionization) can be observed in the redshifted 21cm radiation against the cosmic background in presence of a Ly α background (likely produced by the same sources that reionize the Universe). The expected emission is less than 10 mK (Shaver et al. 1999; Tozzi et al. 2000). However if $T_S \simeq T_K \leq T_{CMB}$, the

HI is visible in absorption with a signal significantly larger than the maximum detectable in emission (see Hogan & Rees 1979). Thus, the most favourable condition for detection is given by a cold IGM in a strong Ly α field.

At the same time, the Ly α photon field also reheats the diffuse gas, driving T_K towards larger values. The thermal history of the diffuse IGM results from the competition between adiabatic cooling and reheating due to the photon field, and it can be simply described as:

$$\frac{dT_K}{dz} = \frac{2\mu}{3} \frac{\dot{E}}{k_B} \frac{dt}{dz} + 2 \frac{T_K}{(1+z)}, \quad (2)$$

where \dot{E} is the heating rate due to recoil of scattered Ly α photons and, possibly, to additional contribution from an X-ray background (here $\mu = 16/13$). The heating is quite efficient, since only 0.004 eV per particle are needed to heat the IGM above the CMB at $z \simeq 10$. Therefore, Ly α resonant scattering or photoelectric heating by soft X-ray photons can reheat the IGM in 10% of the Hubble time (Madau, Meiksin & Rees 1997), and the WT mechanism leads preferentially to emission in the 21cm line.

The signal from high- z HI can be predicted by solving Eq. 1 and Eq. 2, after assuming a value for the Ly α radiation field. A reference value is the thermalization rate $P_{th} = (7.6 \times 10^{-12} \text{ s}^{-1})(1+z)/10$, which is the critical value that would drive T_S towards T_K , and, at the same time, would heat the baryons at a rate of about 200 K per Gyr (see Madau, Meiksin & Rees 1997).

3. 21cm Signatures of Reionization

Between $5 < z_{reion} < 20$ the Universe is expected to experience a phase transition from the neutral to the reionized phase. A first effect of the reionization is the sudden disappearance of the 21cm emission from HI. In fact, Shaver et al. (1999) showed that with a bandwidth of 5 MHz, and an observation of 24 hours, the reionization signal (Figure 1) is detected at 100σ independent of telescope size. For this measure sensitivity is not an issue, the challenge concerns signal contamination. In fact, the sharpness of this feature, expected in the 70–240 MHz range, makes it recognizable from galactic and extragalactic foregrounds (Di Matteo et al. 2001). In addition, Gnedin & Ostriker (1997) computed the 21cm emission in a specific Λ CDM cosmology within an N-body simulation, and showed that the fluctuations in the 21cm emission will dominate the fluctuations in the CMB by two orders of magnitude (Figure 2). The global, all-sky signature of the reionization, can be easily detected by present-day radio telescopes also in the case of a non-homogeneous, patchy process, as in the case of isolated, strong ionizing sources.

Another all-sky, distinctive signature is expected at lower frequencies. A narrow but deep absorption feature would appear in correspondence of the short but significant interval when the Ly α field reach the thermalization value while $T_S < T_K$. The signal computed in the case of heating only by Ly α photons, is shown in Figure 3. Such a strong absorption feature ($\simeq -40$ mK) marks the transition from a cold and dark universe to a universe populated with radiation sources, but not yet reionized. The effect is weakly dependent on the reheating

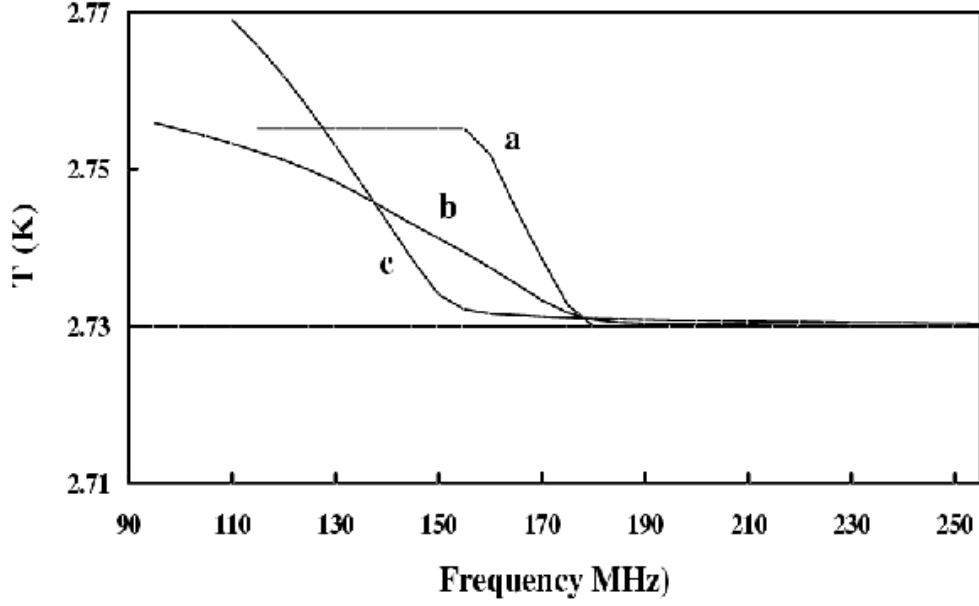


Figure 1. The signal expected from the sudden disappearance of HI, computed as $\delta T_b \simeq (9.0 \text{ mK}) h^{-1} (\Omega_B h^2 / 0.02) [(1+z)/10]^{1/2}$ (from Shaver et al. 1999).

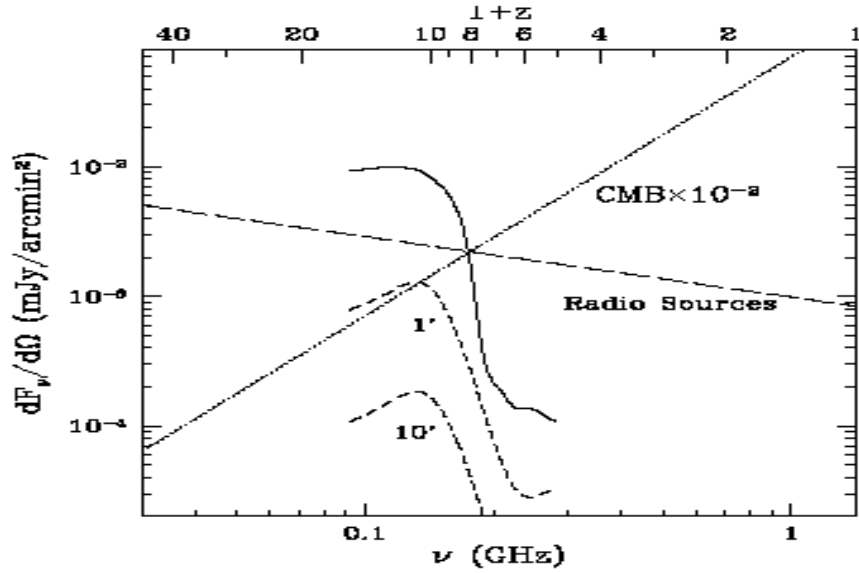


Figure 2. The signal expected from the sudden disappearance of HI, including fluctuations on 1' and 10' scale, computed in a Λ CDM simulation (from Gnedin & Ostriker 1997) and compared with the spectrum of CMB and foreground sources.

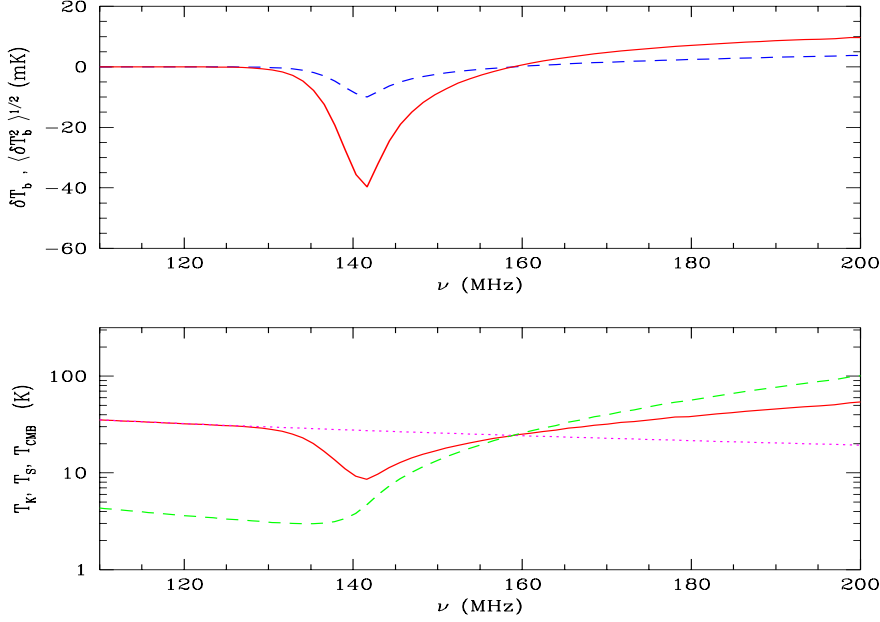


Figure 3. Top: δT_b for a resolution of $1'$ and 1 MHz in frequency, both for the fluctuations (dashed line) and for the continuous distribution of the IGM (solid line), assuming $P_\alpha = P_{th}$ at $z_{th} \simeq 9$ in a critical universe. Bottom: the corresponding T_S (solid) and T_K (dashed) are shown together with T_{CMB} (dotted line).

epoch and on the adopted cosmology. On the other hand, the amplitude of the signal will be strongly dependent on the timescale τ on which the Ly α field reaches the thermalization value. In any case, the maximum of the absorption is always larger than 10 mK (see Tozzi et al. 1999).

Thus, the reheating and reionization epochs are expected to leave a double signature superimposed on the CMB in the 100–200 MHz frequency range. The detailed appearance of such a feature will depend on the spectrum of the ionizing sources. A physical scenario, including a well defined population of sources, can be built with the code CUBA (F. Haardt and P. Madau, see <http://pitto.mib.infn.it/~haardt/cosmology.html>), which provide the evolution of the background radiation to be plugged into Eq. 2.

A tomography of the IGM at high z can be obtained scanning this frequency range. Apart from the all-sky, global signatures that are potentially detectable with a single-dish telescope, an array with a sensitivity of few μJy can detect also the fluctuations in the neutral baryons on scales $> 1'$, corresponding to few comoving Mpc. In the linear regime, the fluctuations induced in the brightness temperature will be directly proportional to $\Delta\rho/\rho$, allowing a straightforward reconstruction of the perturbation field at that epoch. In Figure 4 we show results for two cosmologies, a tilted critical CDM universe (tCDM), and an open $\Omega_0 = 0.4$ universe (OCDM). In both cases the fluctuations are normalized to

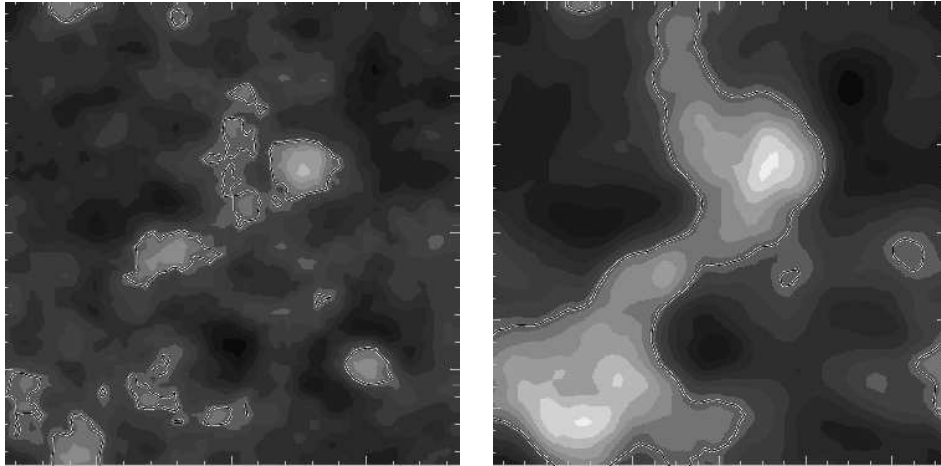


Figure 4. Left: Radio map of redshifted 21cm emission against the CMB in a tCDM cosmology at $z = 8.5$ (beam of $2'$ and bandwidth of 1 MHz). The linear size of the box is $20h^{-1}$ comoving Mpc, corresponding to $17'$ ($11'$) in tCDM (OCDM). The color intensity goes from 1 to $6 \mu\text{Jy}$ per beam. The contour levels outline regions with signal greater than $4 \mu\text{Jy}$ per beam. Right: same for OCDM.

reproduce the local abundance of clusters of galaxies. In OCDM the fluctuations are larger by a factor of 3 since for a given local normalization at $z = 0$, the amplitude of the perturbations at high z is correspondingly larger than that in tCDM. In both figures the density field has been evolved with a collisionless N-body simulation using the Hydra code (Couchman, Thomas, & Pearce 1995), where the baryons are assumed to trace the dark matter distribution without any biasing.

If reheating is provided by a sparse distribution of quasars, 21cm emission on Mpc scales will be produced in the quasar neighborhood (outside the HII bubble) as the medium surrounding it is heated to $T_S = T_K > T_{\text{CMB}}$ by soft X-rays from the quasar itself. The emission region is followed by an absorption ring, since the $\text{Ly}\alpha$ photons reach regions where $T_K < T_{\text{CMB}}$. The size and intensity of the detectable 21cm region will depend on the quasar luminosity and age. The radio map resulting from a quasar ‘sphere of influence’, 10 Myr after it turns on at $z = 8.5$ (tCDM) is shown in Figure 5 (left). The absorption region is limited to a small edge. Moreover, in Figure 5 (right), we show a quasar with the same $\text{Ly}\alpha$ luminosity but with a spectrum absorbed at energies larger than the Lyman limit, as in the case with an intrinsic $N_H > 10^{22} \text{ cm}^{-2}$. Consequently the HII region is reduced, and the X-ray warming front is well behind the light radius. This occurrence leads to a larger absorption ring where the signal reaches $\simeq -40$ mK. In addition, imaging the gas surrounding a quasar in 21cm emission could provide a direct means of measuring intrinsic properties of the source, like the emitted spectrum and the opening angle of quasar emission.

The proposed observations are an obvious target for the Square Kilometer Array (SKA, see <http://www.ras.ualgarny.ca/SKA/science/science.html>). If $\simeq 2/3$ of SKA were reserved for a compact configuration ($\simeq 7$ km in diameter)

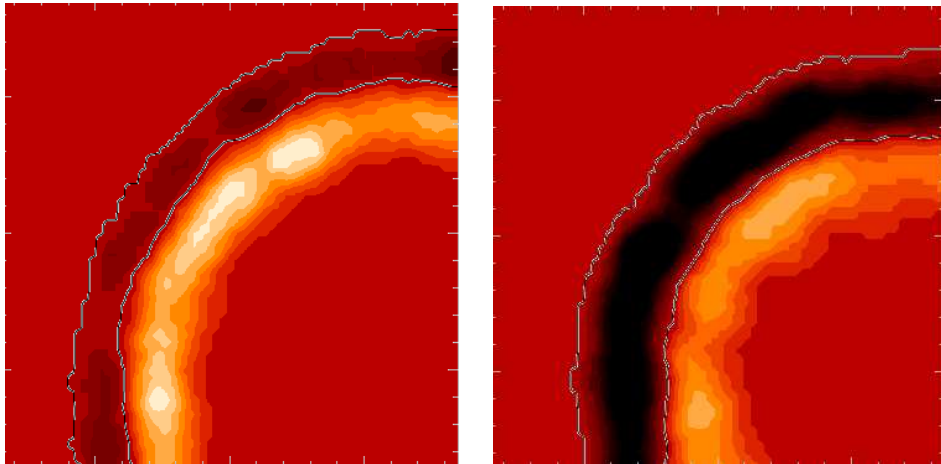


Figure 5. Left: 21cm emission and absorption against the CMB from the region surrounding a quasar. The size of the box is of $20h^{-1}$ comoving Mpc (tCDM; resolution is $2'$, frequency depth 1 MHz). The color levels range from $-3 \mu\text{Jy}$ to $3 \mu\text{Jy}$ per beam. The quasar turns on at $z = 8.5$ with a ionizing luminosity of $10^{57} \text{ photons s}^{-1}$, and is observed after 10 Myr. Right: Same as figure on the left, but the spectrum of the quasar has an exponential cutoff at energies larger than the Lyman limit.

the IGM fluctuations would be detectable at 150 MHz with $1'$ resolution and a bandwidth of 1 MHz, as also quasar emission/absorption shells. In Figure 2 of Tozzi et al. (2000), we showed that a 5σ detection of fluctuations on scales larger than $2'$ can be reached with less than 100 hours of integration.

A potential problem of this kind of observation is the extremely low frequencies involved. To explore the range $10 < z < 20$, where the reheating phase is expected, we need good sensitivity and resolution down to 70 MHz and lower, where technical problems due to the structure of the ionosphere arise and a dedicated instrument is needed. This bandwidth will be observable with the Low Frequency Array (LOFAR). Such observations will have greater probability of detecting the reheating epoch at high z , taking advantage of the strong signal expected during the short epoch when the cold HI reaches its maximum optical depth against the CMB.

As we said above, we do not rely only on future radio facilities. All-sky features or $\simeq 30'$ scale fluctuations (corresponding to $\simeq 1 \text{ mK}$) would be detectable with a small but dedicated telescope, with diameter of about 250 m. A near-future radio facility like the Canadian Large Adaptive Reflector (CLAR, see S. Coté, these Proceedings) would provide a 5σ detection in 300 hours of integration for a typical density fluctuation.

4. Conclusions

The reionization is a crucial epoch in the evolution of cosmic structures. The same ingredients that characterize it (for example: nature of the first sources, the role of black holes in galaxy formation, the role of feedback, the chemical enrichment of the IGM) will deeply affect the evolution of the Universe in the following epochs. Getting direct information about these crucial early stages of the luminous Universe is an obvious goal for the next-decade cosmology. To date, several strategies have been proposed, but most of them must wait for the next generation of astronomical facilities.

The observations of high- z HI in the redshifted 21cm, on the other hand, offer the possibility to investigate the reionization epoch using future but also present-day radio facilities. All-sky signals from HI at redshift $z \simeq 10$ are recognizable as discontinuities superimposed on the CMB in the wavelength range $\simeq 100 - 200$ MHz. In particular, the epoch of reheating can be seen as a deep ($\simeq -40$ mK) absorption feature against the CMB, at the corresponding redshifted 21cm line. The density perturbation field at a redshift $z \approx 5 \div 20$ can be reconstructed looking for mK fluctuations at $1'-5'$ resolution in the radio sky. Finally, luminous quasars can be seen by identifying peculiar, ring-shaped signals whose morphology depends on the source's age, luminosity and geometry. Such observations represent an exciting scientific and technological challenge, and will constitute a unique investigation of the Dark Ages, for many aspects complementary to future observations at other wavelengths.

References

- Barkana, R., & Loeb, A. 2000, *ApJ*, 539, 20
 Barkana, R. 2001, *New Astr.* in press, astro-ph/0108431
 Becker, R.H., et al. 2001, *AJ* in press, astro-ph/0108097
 Couchman, H. M. P. 1985, *MNRAS*, 214, 137
 Couchman, H. M. P., Thomas, P. A., & Pearce, F. R. 1995, *ApJ*, 452, 797
 Di Matteo, T., et al. 2001, *ApJ* in press, astro-ph/0109241
 Djorgovski et al. 2001, *ApJL* in press, astro-ph/0108069
 Field, G. B. 1958, *Proc. I.R.E.*, 46, 240
 Field, G. B. 1959, *ApJ*, 129, 551
 Gnedin, N. Y., & Ostriker, J. P. 1997, *ApJ*, 486, 581
 Hogan, C.J., & Rees, M.J. 1979, *MNRAS*, 188, 791
 Loeb, A., & Rybicky, J. B. 1999, *ApJL*, 524, 527
 Loeb A., & Barkana, R. 2001, *ARA&A*, 39, 19
 Madau, P., Meiksin, A., & Rees, M. J. 1997, *ApJ*, 475, 429 (MMR)
 Rees, M.J. 1999, *Physics Reports*, astro-ph/9912345
 Shaver, P. A., et al. 1999, *A&A*, 345, 380
 Tozzi, P., et al. 1999, *Proc. of the 19th Texas Symposium*, astro-ph/9905199
 Tozzi, P., Madau, P., Meiksin, A., & Rees, M. J. 2000, *ApJ*, 528, 597